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Studies on Digital Shearography for Testing of Aircraft Composite Structures and Honeycomb-based Specimen

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Abstract

This paper reviews shearography and its applications for testing of aircraft composite structures and honeycomb-based specimen. Shearography is a laser-based interferometry in conjunction with the digital imaging processing technique for full-field measurement of surface deformation. It reveals defects in an object by looking for defect-induced deformation anomalies. It does not require special vibration isolation, and with the development of a small and mobile measuring device(portable inspection system), it can be employed easily in field/factory environments.

Keywords: NDT, Shearography, Composite material

1 Introduction

Carbon fiber composite (CFC) and other lightweight constructions are used more and more for the production of aircraft parts. Modern aircraft are already equipped with such components as in the vertical and horizontal stabilizer, rudder, airbrakes and spoiler. Aircraft structures are exposed to severe in-service conditions. In order to receive a high safety of operation, possible damages must be recognized prematurely within control examinations to prevent the total breakdown of the component. Consequently, non-destructive testing (NDT) is a vital process to ensure structural integrity, the investigation with respect to material and construction imperfections is of high interest.

Due to the diversity and complexity of aircraft components, the modern test engineer must become skilled in several complementary inspection methods. Optical NDT is an area that is likely to experience increasing interest for the inspection of composite materials. It offers several advantages over conventional ultrasonic inspection and many of the technical problems that have prevented its industrialization in the past have now been overcome.

The potential advantages of shearography inspection are: (a) rapid large area inspection; (b) non-contact testing without immersion of the component or the use of water jets; (c) ability to inspect regions that attenuate or scatter ultrasound; (d) ability to indicate structural strength in addition to providing passive defect detection[1].

Coherent optical inspection was first devised in 1965 by Powell and Stetson. Industrial exploitation was hampered, however, by the impracticalities of unreliable pulsed lasers and photographic processing of the exposed holograms. Optical inspection moved a step closer to industrialization in 1971 with the advent of a video-based version of holographic interferometry[2]. The technique, known as electronic speckle pattern interferometry (ESPI), is sometimes used industrially for vibration analysis. Unfortunately, ESPI is of limited value for production NDT because its extreme sensitivity to the environment can lead to speckled correlation between the two exposures. Also, rigid-body motion can lead to complex fringe patterns which complicate defect detection. A further breakthrough came in 1979 when Hung developed laser shearography. He demonstrated that optical inspection is feasible in industrial environments if the separate reference beam used in ESPI to encode the phase information of the speckles is replaced by a sheared component of the object beam. The use of sheared wave fronts provides the additional advantage that the fringes depict changes in surface slope, rather than out-of-plane displacement. A principal limitation of shearography is that the interferograms are noisy due to laser speckle and poor signal modulation.

2. Theoretical Analysis

The principle of shearography is shown in Figure 1. Speckle shearography is a reliable coherent-optical method for the nondestructive testing of technical components with respect to surface and sub-surface flaws. In shearography systems, the object under investigation is illuminated by an expanded laser beam, forming a speckle pattern if the object surface is optically rough. The speckle pattern is optically processed by viewing through a shearing interferometer, and the resulting interferogram is recorded by an electronic sensor (e.g. CCD camera). Speckle interferograms, recorded before and after object deformation, are correlated, using a PC, to yield correlation fringes. The phase of these fringes is sensitive to the displacement gradient.

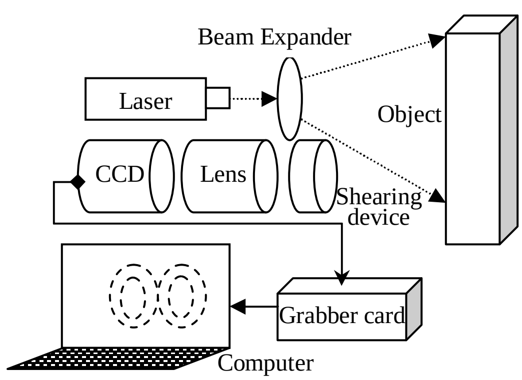

Figure 1. Typical setup of shearography.

The difference of the two intensity distributions I1 (initial state) and I2 (final state after loading) representing the two states to be compared is computed. The special feature of shearography is the generation of the reference wave. By interfering the light that is scattered from the object with its sheared version in the chip plane, the principle of self-reference and consequently insensitivity against rigid body displacements is ensured. A wedge or a prism in front of the sensor lens or a tilted mirror in one arm of a Michelson interferometer are mostly used as shearing component. Detected are only differences of the displacements between the sheared image points. These differences can be approximated as strain components if the shear is sufficiently small. Wollaston lens is used as shearing device in this paper.

One of the important thing for successful application is the combination of the shearography inspection method with choosing the adequate loading method for a given structure to be tested. Loading generates the surface displacement gradient indicating the flaws in the structure. Flaws which can be detected with this method - must weaken the stiffness of the structure: A typical flaw with this characteristic for instance is the delaminations in a CFRP (Carbon Fiber Reinforced Plastic) laminate or the disbond in a bonded metal structure. The response of the object on an applied load depends on several factors: the material, the size and location of the flaw, the structure's stiffness and the way of loading. There are three general types of loading which are mostly selected: (a) vacuum; (b) thermal load using infrared radiators, flash or heat gun, etc[3]; (c) mechanical load caused e.g. by pressure changes in the test environment, or vibration load caused by a shaker.

Real time shearography is performed after the operator captures the first image. Each successive image is compared with this first image. As the object is stressed during the test, the strain changes in the object from the first are displayed as fringes defining the size, shape, and location of the defect or the amount of plane strain. When the operator decides to "freeze" the real time test results, comparing the first image of the test object with these frozen N image, is displayed. Debonded areas in a honeycomb panel will expand out of the plane of the panel, letting the shearographic interferometer detect this localized deformation. The test sequence may be programmed allowing exact replication of the application of the stress level during test.

The resulting intensity distribution before loading $I_1(x,y)$ can be written as

$$\begin{aligned} I_1(x,y) &= U_o^2(x,y) + U_r^2(x,y) + 2U_o(x,y)U_r(x,y)\cos[\varphi_o(x,y) - \varphi_r(x,y)] \\ &= U_o^2(x,y) + U_r^2(x,y) + 2U_o(x,y)U_r(x,y)\cos\Delta\varphi(x,y) \end{aligned} \tag{1}$$

where $U_o(x,y)$ is the amplitude of object light, and $U_r(x,y)$ is the amplitude of reference light. $\varphi_o(x,y)$ is the phase of object light, $\varphi_r(x,y)$ is phase of the reference light.

Some time later, the object is stressed. The resulting intensity distribution is given by

$$\begin{aligned} I_2(x,y) = U_o^2(x,y) + U_r^2(x,y) &+ \\ &2U_o(x,y)U_r(x,y)\cos[\varphi_o(x,y) - \varphi_r(x,y) + \Delta\psi(x,y)] \end{aligned} \tag{2}$$

Here $\Delta\psi(x,y)$ give the phase differences between the phases of the interfering speckle patterns for the first and the second speckle shear interferograms.

The subtraction of the two speckle patterns (i.e. the un-stressed and stressed images) creates a final deformation pattern containing fringes. This resulting pattern can be mathematically described by the following equation:

$$\begin{aligned} I(x,y) &= \left| I_1(x,y) - I_2(x,y) \right| \\ &= 4\left| U_o(x,y)U_r(x,y) \right| \sin[\Delta\varphi(x,y) + \frac{\Delta\psi(x,y)}{2}] \sin\frac{\Delta\psi(x,y)}{2} \end{aligned} \tag{3}$$

Subtraction immediately eliminates the bias term since it is common to both images. The result is a high spatial frequency carrier term $\sin[\Delta\varphi(x,y) + \frac{\Delta\psi(x,y)}{2}]$, amplitude modulated by a low frequency term, $\sin[\frac{\Delta\psi(x,y)}{2}]$. The carrier is nullified when $\sin[\frac{\Delta\psi(x,y)}{2}] = 0$, or, $\Delta\psi(x,y) = 2n\pi$, where the fringe order $n = 0,1,2,3,\Lambda\ \Lambda$. Although $\Delta\psi(x,y)$ retains the sign, or direction, of deformation, carrier nullification occurs identically for positive or negative values; hence, all sign information is lost and fringes depict only the absolute value of the differential displacement.

3. Portable Inspection System

In many cases, for example, maintenance or assembly of aircraft, it is not possible to transport the part to be inspected into a stationary test system. For such purposes, a portable shearography inspection system has successfully been developed and used in filed inspection. In figure 2 and figure 3, such a system is presented. It consists of a heating lamp, which shines directly to the surface to be inspected. Debondings or other defects will show up in typical deformation patterns. The operator can view the inspection result with a notebook pc and therefore is flexible to operate on scaffolds or inside openings.

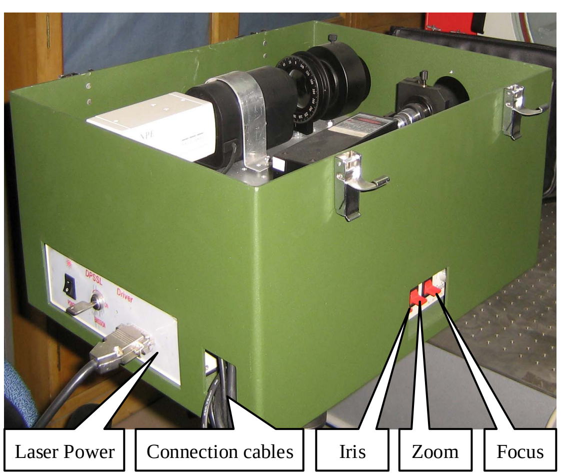

Figure. 2. Outlook of the portable inspection system.

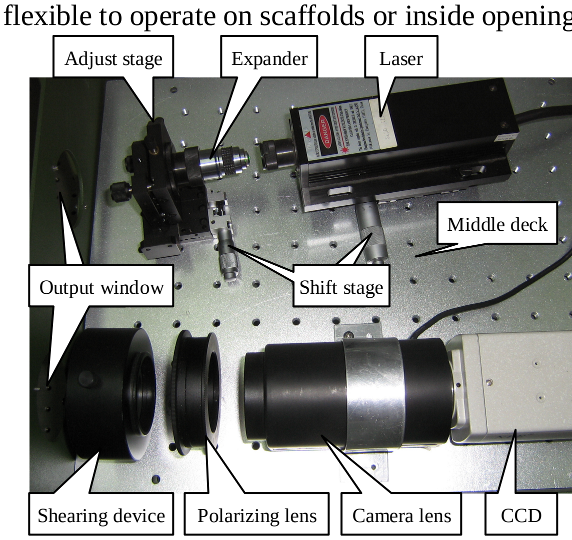

Figure. 3. Layout of upper layer of the portable inspection system.

Figure 4 and figure 5 show the results of the experiment of Specimen A and B. Specimen A: $350\times180\times20$ (mm), skin: glass fiber reinforced plastic, honeycomb: paper, skin-to-core disbonding 30 mm by 30 mm. Specimen B: same size as A, skin: Aluminum, honeycomb: Aluminum, skin-to-core disbonding 20 mm by 20 mm.

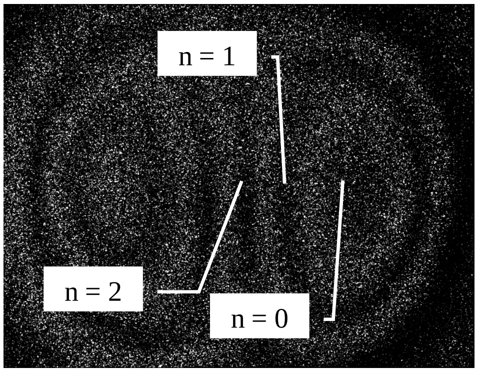

Figure 4. Result of specimen A.

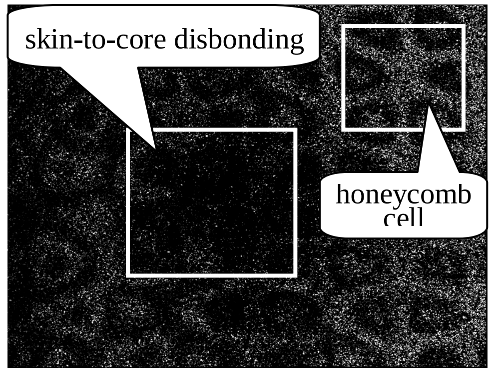

Figure 5. Result of specimen B.

In Figure 4, the dark stripes can show the case when $n = 0,1,2,3,\Lambda\ \Lambda$, that is $\Delta\psi(x, y) = 2n\pi$, as shown in equation 3.

In Figure 5, Each honeycomb cell, measuring by 6 mm by 6 mm, appears as a small double bull eyes in the horizontal direction. The skin-to-core disbonding is shown as a large anomaly.

4 Conclusion

A new highly mobile inspection method has been introduced into the world of in service inspection for maintenance of aircrafts and components under rough industrial conditions. It could be validated, that if optimized, shearography can deal with harsh environmental conditions, can be used really under daylight conditions and still can give precise indications of flaws in a wide variety of inspection situations. The system was demonstrated under real and unusual rough conditions and still showed a great potential to speed up inspection work. New data processing added new possibilities to work with the results, especially to process them with standard software and to give new opportunities to evaluate the data. With the described work a new milestone was set for the acceptance of optical testing in real aircraft maintenance.

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